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Recovery of carbon stocks in deforested caatinga dry forest soils requires at least 60 years

Renisson Neponuceno de Araújo Filho[a], Maria Betânia Galvão dos Santos Freire[a,*], Bradford Paul Wilcox[b], Jason Brossard West[b], Fernando José Freire[a], Flávio Adriano Marques[c]

[a] Department of Agronomy, Federal Rural University of Pernambuco, Av. Dom Manoel de Medeiros, Dois Irmãos, Recife, PE 52171-900, Brazil
[b] Department of Ecosystem Science and Management, Texas A & M University, College Station, TX 77843, USA
[c] EMBRAPA Solos, Rua Antônio Falcão, 402, Recife, PE 51020-240, Brazil

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ABSTRACT

Caatinga forests occupy an area of around one million km^2 in the semiarid region of northeast Brazil. These landscapes are undergoing rapid change because of accelerated deforestation for cultivation and firewood. The capacity of Caatinga forests to regenerate after clearing determines the magnitude of the carbon (C) sink in the soil, and thus is fundamental information for developing management policies for long-term sustainability. The objective of this study was to investigate C stocks and microbial activity in soils of dry Caatinga forests that had undergone harvesting at different times in the past. Soils were collected from three depths (0–5, 5–10, and 10–20 cm) within seven sites representing a sequence of years since cutting: 0.5, 6, 9, 12, 25, 50, and undisturbed (at least 80 years since cutting). Samples from each depth interval were analyzed for total C concentration and stock, humic substances, labile-C, and microbial biomass C. In addition, indicators of microbiological activity, such as basal respiration, microbial quotient, and metabolic quotient, were determined for the two shallow layers. The results showed that C stocks and microbiological activity were strongly influenced by forest cutting times, and reflect significant C losses associated with this type of management. They also suggest that reaccumulation of C following disturbance is slow. Those areas in which the vegetation has remained undisturbed for longer periods have larger C stocks, indicating that long-term maintenance of vegetation increases C storage in soils. For example, 20 years after cutting the C concentrations in soil and humic fractions had recovered to only about 32% of the presumed maximum found for the 80-year site. The average time for C in soil and humic fractions to return to their initial values at these sites is estimated to be approximately 65 years. Even achieving 50% recovery would require at least 33 years between cutting campaigns. Our findings show that in the context of mitigating climate change on a global scale, forest management entities should restrict cutting intervals in semiarid regions such as the Caatinga to longer than 30 years, to allow these soils to rebuild significant C stocks.

1. Introduction

Forests play an important role in mitigating climate change because they store more C than any other terrestrial ecosystem (Dixon et al., 1994). A biome found exclusively in Brazil, the Caatinga forest has not been studied to the extent that Atlantic and Amazonian forests have (Santos et al., 2011). In semiarid northeastern Brazil, Caatinga forests cover an area approximately the size of France and are characterized by deciduous vegetation that is regularly cleared and used for firewood. After clearing, the land is used for itinerant agriculture (Bezerra-Gusmão et al., 2011). Eventually the land is allowed to go fallow and recovery of the forest begins. This practice has been ongoing since Portuguese settlement; however, the period of time between tree harvests has gradually decreased, from over 50 years to as little as 10–15 years currently. Such intense forest management and harvesting of biomass is expected to significantly affect the C stocks in the soil (Nave et al., 2010), especially in areas like the Caatinga forest, already threatened by other drivers of degradation.

Carbon stores in soils are distributed in several organic-matter pools produced by the decomposition of plant, animal, and microorganism biomass. The accumulation, preservation, and loss of soil organic C constitute an important exchange between the biosphere and the

* Corresponding author at: Dom Manoel de Medeiros Street, Campus Universitário de Dois Irmãos, Recife, Pernambuco CEP: 52070-030, Brazil.
E-mail addresses: nepoaraujo@gmail.com (R.N.d. Araújo Filho), mbetaniafreire@uol.com.br, maria.freire@ufrpe.br (M.B.G.d.S. Freire), bwilcox@tamu.edu (B.P. Wilcox), jbwest@tamu.edu (J.B. West), fernando.freire@ufrpe.br (F.J. Freire), flavio.marques@embrapa.br (F.A. Marques).

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atmosphere (Raich and Schlesinger, 1992). Quantification of ecosystem C stocks across disturbance regimes not only helps us understand how a given ecosystem may respond to natural and human disturbances under different management strategies (He et al., 2008), but also enables us to better assess ecosystem potential to sequester C—information that is critical for mitigating global climate change. It is therefore very important to establish a broad database of information on (1) existing C stocks in soils under different plant species and affected by different management strategies, and (2) changes in C stocks over time (Wu et al., 2008).

In addition, changes in the soil environment as a result of disturbance, at both macro and micro scales, affect microbial activity, which affects rates of decomposition of soil organic matter (Anderson and Domsch, 1989). And because microbial biomass can respond more quickly to changes caused by forest management, changes in this biomass can enables us to detect changes in soil C stocks. These changes are also often linked to changes in the chemistry of soil organic C, in particular the proportion of humic substances. In addition to serving as a C reservoir, humic substances improve soil structure, promote soil stability, and regulate soil chemical and biological functions, making them an important contributor to the sustainability of terrestrial ecosystems (Stevenson, 1994).

There have been a few studies addressing the impact of anthropogenic disturbance on Caatinga soil C. Schulz et al. (2016) suggest that grazing causes substantial releases of C from these dry forest soils and argue that better grazing management would lead to higher soil C stocks. Moura et al. (2016) reported that literfall was lowest in recently abandoned pastures, peaked in intermediate regeneration stages, and then slowed in mature (> 50 year old) Caatinga forests. Annual net C accumulation in the ecosystem, however, continued to increase with succession age, as a result of increasing C accumulation in other pools. Althoff et al. (2016) carried out a study of a Caatinga area in Brazil in which tree cutting took place every 10 years at one site, every 15 years at a second site, and every 20 years at a third site, with and without the burning of the residues. They concluded that 50 years was required for C stocks to recover to the levels obtaining before cutting of the vegetation biomass, and therefore the currently recommended cutting cycle of 10–20 years is insufficient.

Given these reported trajectories in ecosystem C fluxes and pools, we hypothesized that following removal of woody vegetation, soil C stocks require over 50 years to recover to their prior levels. The objective this study was to confirm this hypothesis by investigating changes in C content and microbial activity in soils of Caatinga forest areas where woody plant harvesting has taken place at different time intervals.

2. Study area

The study was conducted in a hyperxerophilic Caatinga area (8°30′S and 37°57′W) located in the municipality of Floresta, Pernambuco state, Brazil (Fig. 1). The climate type of this area is BSh semiarid Brazil, characterized as warm and dry (Alvares et al., 2013), with an average annual temperature of 28°C. The average annual precipitation is 500 mm, typically occurring almost entirely between November and March, and the average annual potential evapotranspiration is 1.646 mm. The relief is flat to gently rolling. We selected this area because of the land management practices already in place there and because it possesses a well-defined sequence of forest cutting times. Within the area, we delineated seven experimental sites:

1. The R (reserve) site (08°36.423′S, 37°59.290′W) is an 80-ha parcel that has not been subjected to any kind of anthropogenic interference in the last 80 years. The soil is classified as Haplustepts (Soil Survey Staff, 2014) and the vegetation is dominated by five tree species (a total of 2288 individuals), in the following order of abundance: 30.34% Catingueira (*Poincianella bracteosa* (Tul.) L. P. Queiroz); 26.51% Jurema de Embira (*Mimosa ophthalmocentra* Mart. ex Benth.); 7.05% Quebra Faca Branca (*Croton rhamnifolius* Willd.); 6.27% Maniçoba (*Manihot glaziovii* Müll. Arg.); and 4.98% Pinhão Brabo (*Jatropha mollissima* (Pohl) Baill.) (CPRH, 2000, 2008).
2. The 50-year site (08°30.970′S and 37°59.025′W) is a parcel of 60 ha that has undergone harvesting of forest products for domestic use. The soil class is Haplustepts (Soil Survey Staff, 2014) and the vegetation is dominated by five tree species (a total of 1032 individuals), in the following order of abundance: 34.3% Catingueira (*Poincianella bracteosa* (Tul.) L. P. Queiroz); 11.9% Jurema de Embira (*Mimosa ophthalmocentra* Mart. ex Benth.); 6.4% Pereiro (*Aspidosperma pyrifolium* Mart.); 5.6% Faveleira Braba (*Cnidoscolus bahianus* (Ule) Pax & K. Hoffm.); and 5.3% Angico (*Anadenanthera* colubrina var. cebil (Griseb.) (Altschul) (Alves Júnior et al., 2013).
3. The 25-year site (08°33.416′S and 37°56.548′W) is a 60-ha parcel. This site underwent removal of all vegetation (cutting), and was then abandoned, 25 years before sampling. The soil class is Haplustepts (Soil Survey Staff, 2014), and the five tree species dominating the vegetation (a total of 544 individuals) are as follows: 37.1% Catingueira (*Poincianella bracteosa* (Tul.) L. P. Queiroz); 21.1% Jurema de Embira (*Mimosa ophthalmocentra* Mart. ex Benth); 8.9% Pinhão Brabo (*Jatropha molíssima* (Pohl) Baill.); 5.3% Quipembe (*Pityrocarpa moniliformis* (Benth.) Luckow & R. W. Jobson); and 2.4% Sipaúba (*Thiloa glaucocarpa* (Mart.) Eichler) (Ferraz et al., 2014).

   The four sites cut more recently were treated somewhat differently from the three older sites. Rare trees, protected by law, were preserved. These include: Aroeira *(Myracrodruon urundeuva* Allemão), Baraúna (*Schinopsis brasiliensis* Engl.), Umbuzeiro (*Spondias tuberosa* Arruda), Quixabeira-Braba (*Erytroxylum* sp.), and Imburana de Cambão (*Commiphora leptophloeos* (Mart.) J. B. Gillett). Trees growing along creek and stream borders were preserved as well, as were species not useful for charcoal production and species having a stem diameter of less than 2 cm. All information about these sites comes from existing forest management plans (CPRH, 2000, 2008). Their regeneration has taken place through seed germination and resprouting.
4. The 12-year site (08°35.940′S and 37°59.409′W) is 90 ha. The vegetation at this site was shallow-cut 12 years before sampling. The soil class is Haplustalfs (Soil Survey Staff, 2014), and the five tree species dominating the vegetation (a total of 261 individuals) are as follows, in order of abundance: 25.7% Catingueira (*Poincianella bracteosa* (Tul.) L. P. Queiroz); 11.01% Jurema de Embira (*Mimosa ophthalmocentra* Mart. ex Benth.); 9.29% Maniçoba (*Manihot glaziovii* Müll. Arg.); 8.08% Quebra Faca Branca (*Croton rhamnifolius* Willd.); and 7.41% Aroeira (*Myracrodruon urundeuva* Allemão).
5. The 9-year site (08°35.485′S and 37°59.351′W) is 90 ha. The vegetation at this site was shallow-cut 9 years before sampling. The soil class is Haplustalfs (Soil Survey Staff, 2014), and the five tree species dominating the vegetation (a total of 196 individuals) are as follows, in order of importance: 29.7% Catingueira [*Poincianella bracteosa* (Tul.) L. P. Queiroz]; 8.31% Jurema de Embira (*Mimosa ophtalmocentra* Mart. ex Benth.); 8.1% Quipembe [*Pityrocarpa moniliformis* (Benth.) Luckow & R. W. Jobson]; 7.3% Quebra Faca Branca (*Croton rhamnifolius* Wild.); and 6.02% Aroeira (*Myracrodruon urundeuva* Allemão).
6. The 6-year site (08°34.665′S and 38°00.910′W) is 90 ha. The vegetation at this site was shallow-cut 6 years before sampling. The soil class is Haplustepts (Soil Survey Staff, 2014), and the five tree species dominating the vegetation (a total of 131 individuals) are as follows, in order of abundance: 36.31% Catingueira (*Poincianella bracteosa* (Tul.) L. P. Queiroz); 10.69% Jurema de Embira (*Mimosa ophthalmocentra* Mart. ex Benth.); 9.7% Pinhão Brabo (*Jatropha mollissima* (Pohl) Baill.); 5.08% Aroeira (*Myracrodruon urundeuva* Allemão); and 5.02% Pereiro (*Aspidosperma pyrifolium* Mart.).
7. The 0.5-year site (08°35.518′S and 37°59.741′W) is 90 ha. The

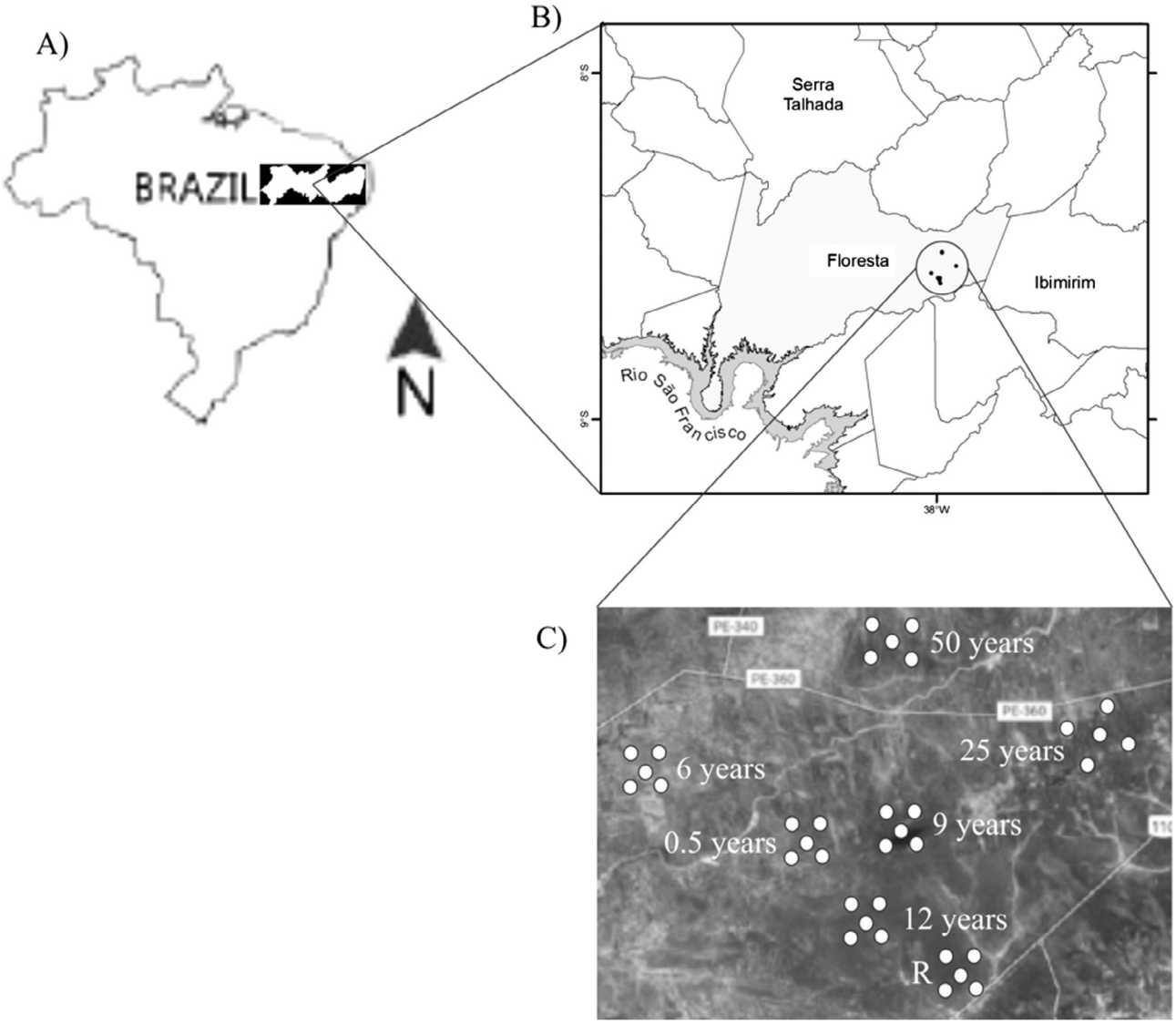

Fig. 1. (A) Pernambuco state in Brazil; (B) Floresta municipality; and (C) locations of Caatinga study sites.

vegetation at this site was shallow-cut recently (six months before sampling). The soil class is Haplustalfs (Soil Survey Staff, 2014), and the five species dominating the vegetation (a total of 131 individuals) are as follows, in order of abundance: 29.7% Catingueira (*Poincianella bracteosa* (Tul.) L. P. Queiroz); 20.1% Jurema de Embira (*Mimosa ophthalmocentra* Mart. ex Benth.); 10.69% Aroeira (*Myracrodruon urundeuva* Allemão); 10.1% Quipembe (*Pityrocarpa moniliformis* (Benth.) Luckow & R. W. Jobson); and 8.31% Pinhão Brabo (*Jatropha mollissima* (Pohl) Baill.).

3. Materials and methods

3.1. Soil sampling

In each of the seven experimental sites, five trenches measuring 20 × 50 × 30 cm deep were excavated at 50-m intervals. Soil samples were collected from these trenches at depths of 0–5, 5–10, and 10–20 cm, with five repetitions (trenches) per site. The soil samples to be analyzed for physical and chemical properties were air dried and passed through a 2-mm-mesh sieve to remove large fragments of rocks and undecomposed organic matter. For bulk density analysis, samples of undisturbed soil were collected in the same trenches, by steel ring. The samples were protected by plastic film and wrapped in plastic bubble packaging for transportation to the laboratory. For the microbiological analysis, soil samples were collected only from the 0–5-cm and 5–10-cm depth intervals; these were stored in plastic bags and kept refrigerated, in the field and in the laboratory, until the analyses were done.

3.2. Physical analysis

Table 1 shows the results of the soil physical properties analyses for each of the seven experimental sites. Deformed soil samples were used to determine particle size distribution, via the pipette method as modified by Ruiz (2005). To each 10-g sample was added 50 mL of NaOH solution of 0.1 mol L^{-1} and 150 mL of deionized water; the mixture was stirred with a glass rod and left to settle overnight. The mixtures were then dispersed by shaking at 12,000 rpm for 15 min, after which the suspension was passed through a 0.053-mm sieve. Silt and clay fraction was collected in a 500-mL graduated cylinder and shaken again. Immediately afterward, we collected 25 mL of the silt + clay suspension and allowed it to settle for the time calculated by Stokes' Law for the ambient temperature. Then we collected another 25 mL of the suspension from 5 cm below the surface (clay fraction). All fractions were oven-dried at 100 °C and weighed to calculate the percentages of coarse sand, fine sand, silt, and clay.

Soil samples for bulk density measurements were obtained by the

Table 1
Soil physical properties for the seven experimental sites in the sequence of clear-cutting times of Caatinga forest (based on sampling at three depth intervals[a]).

Site	Sand	Silt	Clay	Bulk density	Texture
	%			kg dm^{-3}	
0–5 cm depth interval					
80 years[b]	43.89 ± 1.23	32.72 ± 0.71	23.39 ± 1.41	1.18 ± 0.05	Loam
50 years	58.59 ± 1.19	15.90 ± 1.10	25.50 ± 1.84	1.20 ± 0.02	Sandy clay loam
25 years	77.83 ± 1.38	7.39 ± 1.37	14.76 ± 1.38	1.44 ± 0.02	Sandy loam
12 years	66.32 ± 1.00	18.38 ± 1.72	15.29 ± 2.55	1.69 ± 0.02	Sandy loam
9 years	65.78 ± 1.63	17.62 ± 1.21	16.58 ± 1.03	1.68 ± 0.01	Sandy loam
6 years	78.37 ± 2.02	6.98 ± 2.07	14.64 ± 1.53	1.42 ± 0.09	Sandy loam
0.5 year	63.18 ± 3.10	19.13 ± 3.36	17.67 ± 2.21	1.67 ± 0.06	Sandy loam
5–10 cm depth interval					
80 years	43.66 ± 2.04	33.48 ± 1.88	22.85 ± 2.10	1.36 ± 0.02	Loam
50 years	58.58 ± 0.83	15.81 ± 0.98	25.60 ± 1.45	1.30 ± 0.05	Sandy clay loam
25 years	79.32 ± 0.53	6.33 ± 2.17	14.33 ± 1.67	1.53 ± 0.02	Sandy loam
12 years	62.40 ± 0.54	19.89 ± 0.29	17.69 ± 0.71	1.74 ± 0.01	Sandy loam
9 years	68.06 ± 1.67	18.88 ± 0.97	16.05 ± 1.06	1.70 ± 0.01	Sandy loam
6 years	78.34 ± 1.40	6.73 ± 2.27	14.92 ± 1.26	1.50 ± 0.05	Sandy loam
0.5 year	66.22 ± 1.70	17.54 ± 2.80	16.23 ± 2.03	1.69 ± 0.05	Sandy loam
10–20 cm depth interval					
80 years	48.90 ± 0.95	26.50 ± 1.52	24.57 ± 3.21	1.41 ± 0.04	Sandy clay loam
50 years	60.72 ± 4.23	14.57 ± 0.37	24.69 ± 3.24	1.39 ± 0.11	Sandy clay loam
25 years	79.98 ± 2.29	6.39 ± 0.51	13.61 ± 1.90	1.57 ± 0.03	Sandy loam
12 years	55.88 ± 2.19	14.58 ± 1.06	29.53 ± 2.28	1.75 ± 0.01	Sandy clay loam
9 years	54.93 ± 1.03	15.30 ± 1.14	29.75 ± 0.98	1.74 ± 0.02	Sandy clay loam
6 years	79.04 ± 1.37	6.50 ± 1.05	14.45 ± 1.59	1.52 ± 0.05	Sandy loam
0.5 year	54.90 ± 2.04	16.21 ± 1.36	28.87 ± 1.72	1.72 ± 0.01	Sandy clay loam

[a] Average values in soils under Caatinga forest at different times after clear-cutting.
[b] Reserve area.

volumetric ring method: stainless steel rings (5 cm in diameter and 10 cm long) were used to collect samples from zones of undisturbed soil. Bulk density was calculated on the basis of the soil mass inside the ring and the volume of the ring. At the 50-year site, where it was not possible to insert the rings into the soil, clod samples were collected and analyzed via the paraffin clod method (Blake and Hartge, 1986).

3.3. Chemical and carbon analysis

To determine the concentrations of fulvic acid (FA), humic acid (HA), and humin (H), we performed chemical fractionation of the humic substances in accordance with the International Humic Substances Society method, which is based on solubility in acidic and alkaline solutions (Swift, 1996). After fractionation, the samples were frozen and lyophilized. The fraction of light organic matter (LOM—organic matter having a density of less than 1 kg dm^{-3}) was separated out by the water flotation method, as modified by Fraga and Salcedo (2004): 50-g soil samples were first passed through a 0.5-mm-mesh sieve, then placed on a 0.053-mm-mesh sieve and washed under running water until the solution came out limpid (indicating complete removal of silt and clay fractions). The material remaining on the sieve was transferred to a 500-mL beaker, the beaker was filled with distilled water, and the solution was stirred with a glass rod until the LOM stayed suspended in the water. The suspension was left to stand for 24 h, until it became limpid; then the material that had filtered out was collected, placed in a 0.053-mm-mesh sieve, washed with distilled water, and dried in an air-forced circulation stove at 60°C until constant weight was attained (as determined via analytical balance). After drying, the samples were macerated with a porcelain mortar and pestle until the powder was fine enough to pass through 150-μm-mesh. This powder was used for the C measurements, done via the combustion method (CHNS/O) in an elemental analyzer (Model PE-2400 Series II, Perkin Elmer).

Concentrations of labile carbon (labile-C) were estimated via oxidation with potassium permanganate solution ($KMnO_4$) 0.033 mol L^{-1} (Blair et al., 1995). These concentrations were then converted to Mg ha^{-1}, representing the C stock for each sampled depth interval, as follows:

$$C_{STOCK} = \frac{TOC_{SOIL} \times BD \times h}{10},$$

where TOC_{SOIL} is the concentration found by analysis of soil samples (g kg^{-1}), BD is the bulk density (kg dm^{-3}), and h is the thickness of the soil in the sampled depth interval (cm).

The C stock values for the three depth intervals were summed to obtain a total C stock value for the 0–20-cm soil layer (except for microbial biomass carbon [MBC], the value for which was derived from the 0–10-cm depth interval).

3.4. Microbiological analysis

The microbiological analyses consisted of basal respiration (BR) (Isermeyer, 1952) and MBC. We used the irradiation extraction method, with a power microwave oven (900 W and 2450-MHz frequency), in accordance with the protocol of Islam and Weil (1998). The C extracts were determined from irradiated and non-irradiated samples via the colorimetric method (Bartlett and Ross, 1988); the metabolic quotient (qCO_2) was obtained by dividing the BR value by the MBC value (Anderson and Domsch, 1985); and the microbial quotient (qMIC) was obtained by dividing MBC by soil C.

3.5. Statistical analysis

The analytical results for the different parameters were subjected to analysis of variance (ANOVA) and compared at $P < 0.05$. When the variable of time since cutting was significant for the parameter we applied adjusted regression equations to our Caatinga forest sequence of years since cutting, which enabled us to estimate recovery time for each of the soil parameters. On the basis of these estimates, we determined an expected proportion of recovery of each parameter as a function of time since cutting. This information will be very useful for establishing timetables for Caatinga forest management.

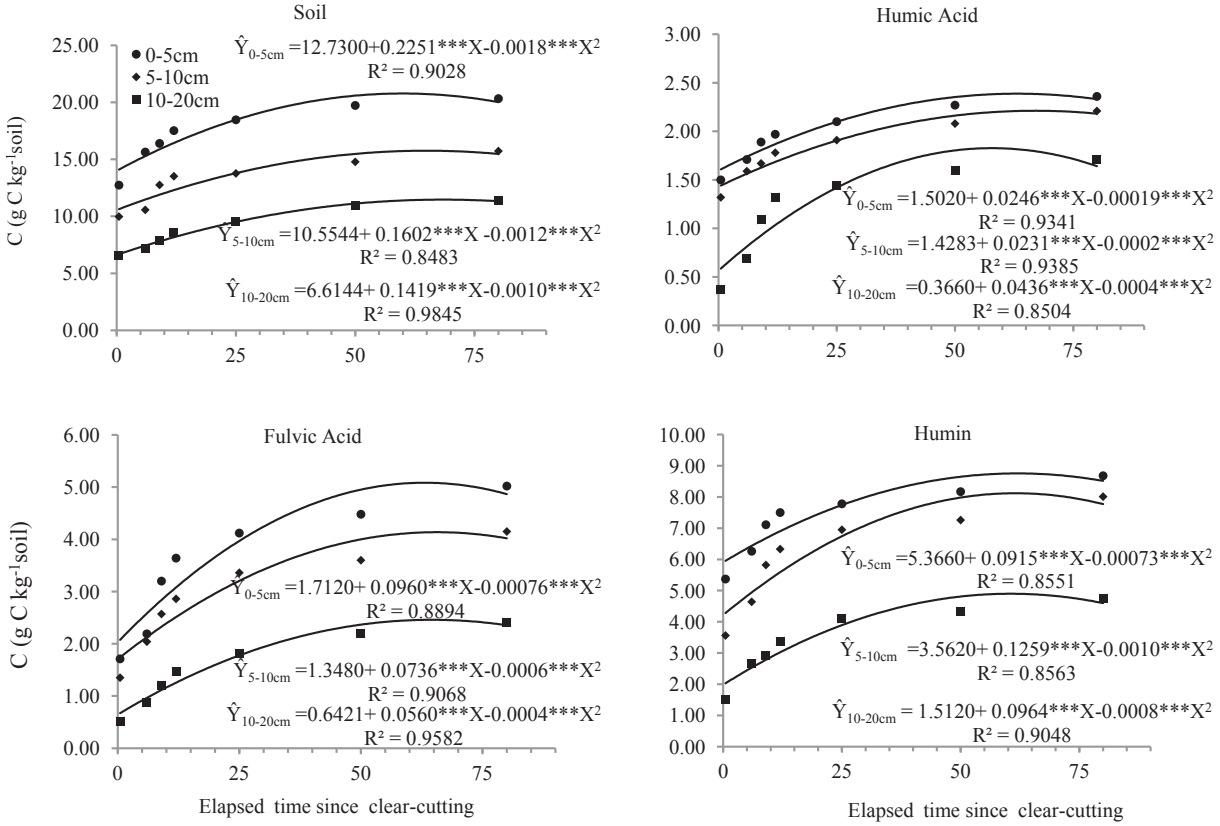

Fig. 2. Carbon concentrations in whole soil and in soil humic fractions for the depth intervals 0–5, 5–10, and 10–20 cm along the sequence of clear-cutting times of Caatinga forest. Significant results are indicated by $^{***}(P < .001)$.

4. Results

4.1. Carbon concentrations in soil and humic substances

Average C concentrations in the seven Caatinga forest experimental sites varied according to the time elapsed since cutting of the vegetation (Fig. 2). For all the depth intervals, C concentrations in soils and in humic substances increased nonlinearly with time since cutting. For all the sites at all depths, the largest fraction of the humic substances was humin (Fig. 2). The fulvic acid fraction was higher in C content than the humic acid fraction (Fig. 2).

4.2. Carbon stocks in soil and humic substances

Carbon stocks in soil greatly influence soil physical and chemical properties. In the Caatinga forest sites we studied, there were significant, quadratic increases in C stocks, in soils and in humic substances, as time since cutting increased. The average C stock in the 0–20-cm depth interval for the 0.5-year (most recently cut) site was 27.57 Mg C ha^{-1}, compared with 45.21 Mg C ha^{-1} for the Reserve (undisturbed vegetation) site (Fig. 3).

Most of the soil C stock appears be associated with the humin fraction (Fig. 3).

4.3. Labile-C concentrations in soil and carbon stocks in labile and microbial biomass fraction

Labile-C is that constituent of organic compounds more easily mineralized by soil microorganisms. We found that—in parallel with total soil C—labile-C increased significantly at all depths along the Caatinga forest cutting-times sequence, with the highest levels recorded in the upper (0–5 cm) depth interval (Fig. 4). In our Caatinga forest study area, the distribution of labile-C varied as a function of time since cutting, in parallel with changes in soil C (Fig. 4). The proportions of labile-C relative to soil C were 7.1–11.2% for the 0–5-cm depth interval; 8.9–14.5% for the 5–10-cm depth interval; and 8.7–14.9% for the 10–20-cm depth interval.

For all the soil depth intervals, there was a significant relationship between time since cutting and increases in both C stocks in the labile fraction and high increase in microbial biomass over the observed timeframe (Fig. 5). Of particular note is the continued high rate of increase between 25 and 50 years since cutting, indicating ongoing recovery during this time period.

4.4. Carbon in light organic matter

It is expected that there will be a proportional relationship between total soil C and the amount of C in the free light fraction of organic matter, since the light fraction is intermediate between organic matter residues from plants and humified soil organic matter. We found that the C content in the free light fraction varied with time since cutting and varied with depth, ranging from 0.351 to 0.594 g kg^{-1} in the 0–5-cm depth interval, from 0.318 to 0.562 g kg^{-1} in the 5–10-cm depth interval, and from 0.239 to 0.472 g kg^{-1} in the 10–20-cm depth interval (Fig. 6).

4.5. Microbiological activity

The indicators of microbiological activity that were evaluated in this study—MBC, BR, and *q*MIC— also increased quadratically with time since cutting, in large increments, and possibly reached an equilibrium after a long period (Fig. 7).

Concentrations of MBC ranged from 110.01 to 435.10 mg kg^{-1} for the 0–5-cm depth interval and from 60.09 to 380.02 mg kg^{-1} for the

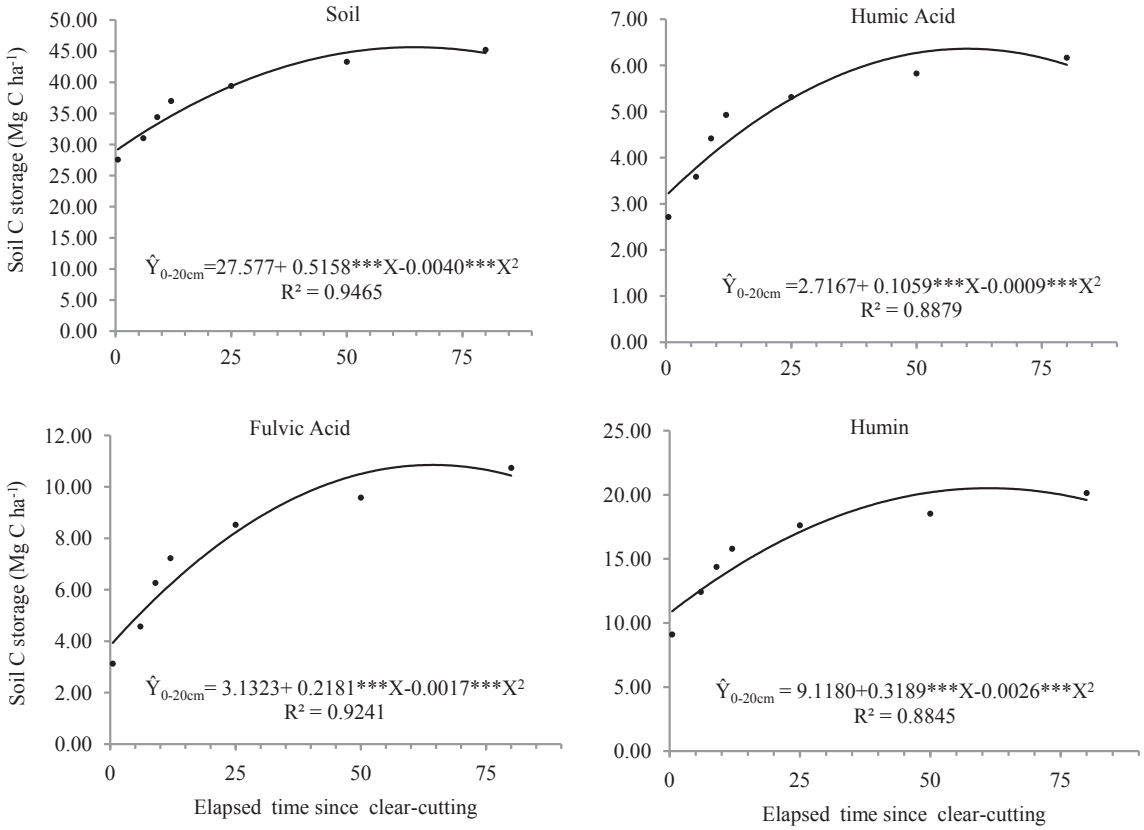

Fig. 3. Carbon stocks in whole soil and in soil humic fractions for the 0 to 20 cm depth interval along the sequence of clear-cutting times of Caatinga forest. Significant results are indicated by ***(P < .001).

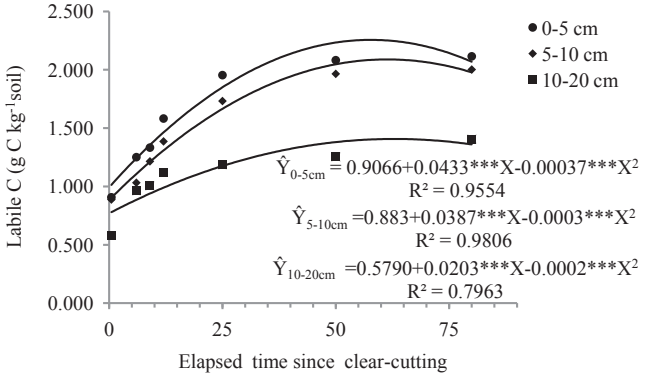

Fig. 4. Concentrations of labile-C for the 0–5-cm, 5–10-cm, and 10–20-cm depth intervals along the sequence of clear-cutting times of Caatinga forest. Significant results are indicated by ***(P < .001).

5–10-cm depth interval (Fig. 7) and were significantly reduced by degradation (the growth of microorganisms is limited by the availability of organic substrates).

Basal respiration followed the same pattern as MBC, with values ranging from 0.50 to 0.75 mg CO_2-C kg^{-1} soil h^{-1} for the 0–5-cm depth interval and from 0.25 to 0.59 mg CO_2-C kg^{-1} soil h^{-1} for the 5–10-cm depth interval (Fig. 7). As with microbial biomass, it is important to emphasize that BR rates continued to increase even after the 50-year recovery time point. The results from these two depth intervals show that the contribution of MBC to soil C (qMIC) was remarkable, representing around 1% of average soil C (Fig. 7). At the recently cleared sites this value was higher in the 0–5-cm depth interval, whereas for the sites that had not been cleared for long periods (25 years, 50 years, and 80 years) the highest *q*MIC values were observed in the 5–10-cm depth interval (Fig. 7).

The qCO_2 values along the Caatinga forest cutting-times sequence showed a decrease, a common post-disturbance result for areas undergoing periodic cutting (Fig. 7).

4.6. Recovery time

To estimate C recovery times for Caatinga forest soils, we used the quadratic equations from our statistical analysis. We adjusted these equations for each variable in each of the three soil depth intervals to determine the times required for a 50% recovery of C levels and for a 100% recovery (Table 2).

Some C variables require more time for recovery than others. The variable showing the longest recovery times is BR, especially in the 5–10-cm depth interval: 44 years for 50% recovery and 88 years for 100% recovery. The variable showing the shortest recovery times is labile-C in the 10–20-cm depth interval: 26 years for 50% recovery and 51 years for 100% recovery.

5. Discussion

5.1. Carbon concentrations in soil and humic substances

We observed (1) an overall increase in soil C concentrations, for all fractions at all depths, as time since forest cutting increased; and (2) a decline in soil C with depth for all time since cutting. The higher C concentrations in soil and humic substances for the shallowest depth interval can be attributed to surface and below-ground litter inputs and root exudation. Incorporation of plant biomass into the soil accounts for most of the contributions of C compounds and for the increasing C stocks in most of the humic fractions. In a study of the dynamics of soil organic C stocks in a Guinea savanna, Bessah et al. (2016) reported that C concentration decreased with increasing depth, regardless of land use

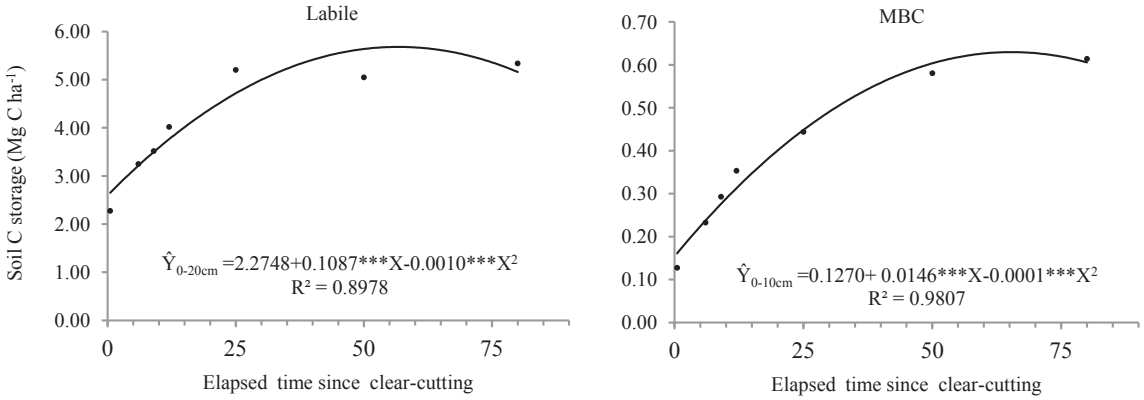

Fig. 5. Carbon stocks in labile and MBC fractions along the sequence of clear-cutting times of Caatinga forest. Significant results are indicated by $^{***}(P < .001)$.

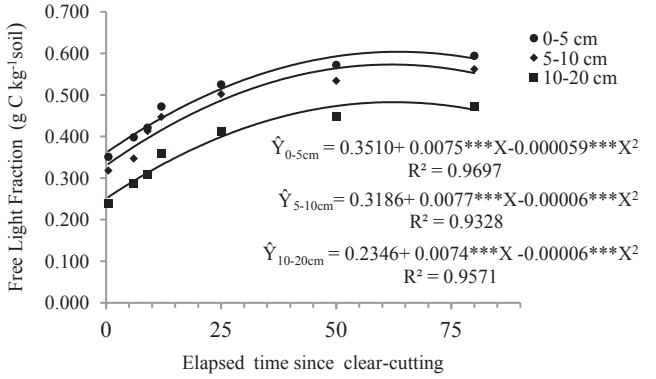

Fig. 6. Concentrations of C in the light fraction of soil organic matter for the depth intervals 0–5, 5–10, and 10–20 cm along the sequence of clear-cutting times of Caatinga forest. Significant results are indicated by $^{***}(P < .001)$.

change. Barros et al. (2015) also observed a decrease in soil C concentration with depth, mainly below 20 cm in areas of the Caatinga where the vegetation had remained undisturbed.

Increases in C concentrations with time since cutting reflect a unbalance between C inputs and outputs during the periods of undisturbed vegetation growth. Other factors may include biochemical recalcitrance of vegetation compartments and limited supplies of the water and nutrients needed for decomposition of organic matter inputs. The higher levels of soil C found with greater forest age are associated with greater plant biomass and microbial activity, which promote the incorporation and stabilization of organic matter over time.

Tropical climate soils in general are associated with rapid decomposition of organic matter and limited accumulation in soil (Qiu et al., 2015). This high decomposition rate is facilitated by favorable climatic conditions (warm temperatures and moist soils) and high soil microbial activity (Giongo et al., 2011). Although the rainy season in the Caatinga is short (generally lasting four months—Sampaio, 1995), it provides ideal conditions for high decomposition of organic matter, especially in

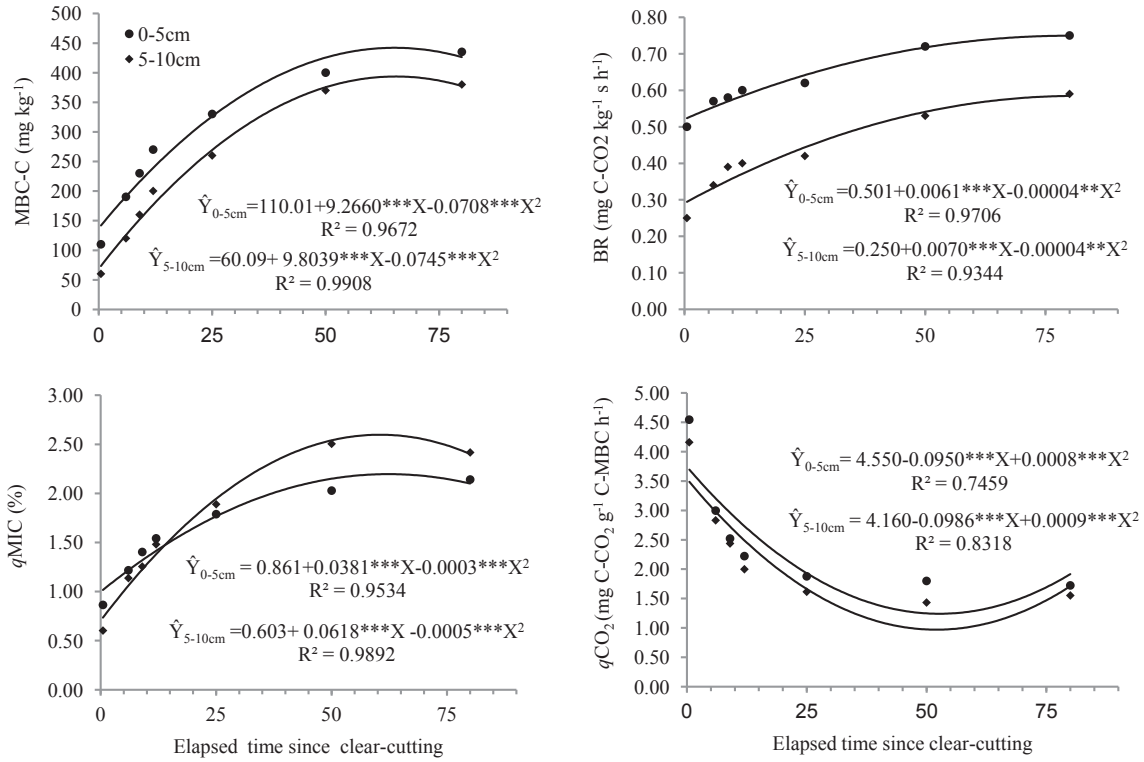

Fig. 7. Microbial biomass carbon (MBC), basal respiration (BR), microbial quotient (*q*MIC), and metabolic quotient (qCO_2) for the depth intervals 0–5 and 5–10 cm along the sequence of clear-cutting times of Caatinga forest. Significant results are indicated by $^{**}(P < .01)$ or $^{***}(P < .001)$.

Table 2
Estimated time required for soil C variables to achieve various levels of recovery.

Variable	Depth interval (cm)	Recovery time (years) to various levels					
		50%	60%	70%	80%	90%	100%
Total organic C (TOC)	0–5	32	38	44	51	57	63
	5–10	34	41	47	54	61	67
	10–20	36	43	50	57	64	71
Fulvic acid C (FA-C)	0–5	32	38	45	51	57	64
	5–10	31	37	43	50	56	62
	10–20	35	42	49	56	63	70
Humic acid C (HA-C)	0–5	33	39	46	52	59	65
	5–10	29	35	41	47	52	58
	10–20	28	33	39	44	49	55
Humin C (HUM-C)	0–5	32	38	44	51	57	63
	5–10	32	38	45	51	57	63
	10–20	31	37	43	49	55	61
TOC Stock	0–20	33	39	46	52	59	65
FA-C Stock	0–20	30	36	42	48	53	59
HA-C Stock	0–20	33	39	45	52	58	65
HUM-C Stock	0–20	31	37	43	50	56	62
Labile-C	0–5	30	36	41	47	53	59
	5–10	33	39	46	52	59	65
	10–20	26	31	36	41	46	51
Labile-C Stock	0–20	28	33	39	44	49	55
MBC Stock	0–10	37	44	52	59	66	73
L - Light organic matter C	0–5	32	39	45	51	58	64
	5–10	33	39	45	52	58	65
	10–20	31	37	44	50	56	62
Microbial biomass C (MBC)	0–5	33	40	46	53	59	66
	5–10	33	40	47	57	60	66
Microbial quotient (qMIC)	0–5	32	39	45	51	58	64
	5–10	31	38	44	50	56	62
Basal respiration (BR)	0–5	39	46	54	61	69	77
	5–10	44	53	62	70	79	88
Metabolic quotient (qCO_2)	0–5	30	36	42	48	54	60
	5–10	28	33	39	44	50	55
Average		32	39	45	51	57	64

soils lacking a significant forest canopy. Our results suggest that soil C pools can be rapidly lost from these ecosystems and that their recovery times may be quite long.

Fraga and Salcedo (2004) found that C concentrations in undisturbed Caatinga forest were nearly twofold higher than in degraded areas (17.8 g kg^{-1} vs 8.9 g kg^{-1} for 0–7.5-cm depths). In our study, we found values ranging from 20 g kg^{-1} for the 0–5-cm depth interval at the Reserve site to 13 g C kg^{-1} at the 0.5-year site. Although not specifically considered degraded, the soils in our study exhibited patterns similar to those reported by Fraga and Salcedo (2004), albeit with somewhat higher C concentrations.

In addition to total organic C, it is important to know the distribution of C in the organic fractions of soil. In all the study sites and in every depth interval, humin was the dominant humic-substances fraction. Organic matter in this fraction is considered more recalcitrant and stable, in part because of associations between C compounds and the mineral matrix of the soil (Stevenson, 1994; Aranda and Comino, 2014). Because of its solubility properties, humin is also considered to be the most important fraction in terms of C sequestration; the formation of strong bonds between humin and soil minerals impedes the ability of microbes to aid in decomposition (Moraes et al., 2011).

The fulvic acid fraction had the next-highest C content, followed by humic acid. This can be explained partly by the polyphenol theory—that the formation of fulvic acid occurs before that of humic acid (Stevenson, 1994). Having a simple structure of low molecular weight and being soluble in water under all pH conditions, fulvic acid is the first of the humic substances to form and is subsequently altered to form humic acid (Dou et al., 2003). According to Canellas et al. (2007), a larger proportion of fulvic acids in a soil indicates that the humus is higher quality and that biological activity is robust. The predominance of fulvic acids in Caatinga soils may indicate the presence in this region of high-quality organic compounds for C cycling. However, the solubility of fulvic acids makes them susceptible to losses by leaching, and thus a shorter residence time in soils.

The compounds in humic acid are more complex than those of the other two fractions; they are arranged in supramolecular structures and consist of hydrophobic and amphiphilic compounds of low molecular weight that result from the deterioration and decomposition of biological material (Sutton and Sposito, 2005). Cheng and An (2015), in studies of C concentrations in succession vegetation on the semiarid Loess Plateau of China, found that C concentrations in humic substances (0–20-cm depth interval) increased with vegetation recovery time, but the increase in the humic acid fraction was the lowest— from 0.7 to 1.9 g kg^{-1}—vs 0.5 to 2.9 g kg^{-1} for fulvic acids and 1.5 to 4.3 g kg^{-1} for humin. These differences in total C storage by the different fractions suggest that where concentrations of non-recalcitrant compounds are significant, vulnerability to C losses is higher.

5.2. Carbon stocks in soil and humic substances

In the Caatinga forest sites we studied, C stocks in both soils and humic substances increased significantly and nonlinearly with time since cutting—the larger increases being seen in the humic substances. Of the three fractions, humin appears to contain most of the accumulated soil C stock, likely because it is the most recalcitrant in soils; it becomes concentrated in the clay component, where it forms organic mineral complexes (demonstrating the potential of these soils as C sinks). The higher the quantity of humin, the more will C stocks be maintained and augmented.

Tiessen et al. (1998) estimated the C stock in the top 20 cm of tropical soils in semiarid northeastern Brazil as 20 Mg C ha^{-1}. Schulz et al. (2016), studying whether grazing contributed to the deterioration of soil C stocks in Caatinga forest ecosystems, reported an average soil organic C stock of 17 Mg C ha^{-1}, of which approximately one-quarter was found in the upper 5 cm of the soil profile. Moura et al. (2016) studied C cycling in four different stages of forest succession (ranging from 1 to 57 years) in Paraíba, Brazil. The authors reported a higher soil C stock in the 0–20-cm depth for the later stages of succession, with values ranging from 22 Mg C ha^{-1} for 1 year to 37 Mg C ha^{-1} for 57 years since cutting. Although these results seem intuitive and are consistent with our findings, Gamboa et al. (2010) reported no significant increases of soil C stock associated with a transition from early to late succession in a dry forest in Mexico; however, after the addition of fertilizer they did observe an increase, suggesting that lack of nutrients was limiting the accumulation of soil C. The fact that no fertilizer was used in our study supports the validity of our results, which are consistent with continued accumulation of C as Caatinga forests recover from prior harvests—at least for the first 50 years of recovery.

5.3. Labile-C concentrations in soil

At all seven of our study sites, the highest amounts and greatest changes in content of labile-C were observed in the upper (0–10 cm) depth interval. There was also a significant, positive relationship between C stocks in the labile fraction and time since cutting for all the soil depth intervals. This is consistent with increasing inputs of aboveground plant litter and turnover/exudation of fine roots in the surface soils (Sierra et al., 2013). According to Blair et al. (1995), labile-C in soils is expected to decrease in areas that have recently undergone vegetation management. Wang et al. (2010), studying the spatial

variability of soil organic C and stocks of C in the hilly area of the Loess Plateau, China, found that for all types of land use, labile-C concentrations decreased with depth in the soil profile.

We agree with the observation by Blair (2000) that maintenance of soil C stocks, especially the labile-C fraction, is essential for the maintenance of soil quality and the sustainability of dry forest ecosystems. Studies done in various regions have reported a fairly wide range of proportions of labile-C to total C in soils: results range from 14 to 25% in Ustalfs in a semiarid region of Australia (Lefroy et al., 1993), 17 to 27% in three Australian soil classes (Blair et al., 1995), and up to 50% in Ustox soils in a semiarid region of Pernambuco-Brazil (Shang and Tiessen, 1997). We found smaller proportions in the soils of our experimental sites (10% or less); we believe can be attributed at least in part to the coarse textures of these soils, which makes them more susceptible to losses of labile-C during rainy seasons. In addition, as noted below, we observed high metabolic quotients, particularly for the recently harvested sites, which would also tend to drive losses of labile-C via heterotrophic respiration.

5.4. Carbon in light organic matter

Under conditions of undisturbed vegetation, a large proportion of the light organic matter fraction is contained within soil aggregates and is thereby protected against losses by erosion and mineralization (Cambardella and Elliott, 1994). When vegetation is removed, the light fraction is lost faster than the most protected fraction (Magid and Kjaergaard, 2001). Our results are consistent with this finding, showing that the organic matter light fraction has increased with time since cutting and was lowest at the most recently cleared site. Christensen (1992) states that accumulation of the light fraction of organic matter is a function of vegetation management, vegetation type, and other factors that alter the balance between production and decomposition of organic matter. According to Janzen et al. (1992), under relatively arid conditions, the light fraction tends to decompose at slower rates and to accumulate to higher levels. At the same time, the high year-round temperatures in Brazilian semiarid regions may be creating conditions favorable to quick decomposition of organic matter, at least when soils are relatively moist.

5.5. Microbiological activity

The indicators of microbiological activity increased quadratically with time since cutting. The incorporation of plant residues into the soil over time improves both chemical and physical soil conditions and thus promotes an increase in microbial biomass (Pimentel et al., 2011). This process was evident in the upper depth intervals of our sites, which exhibited higher levels of biological activity. According to Pacchioni et al. (2014), microbial diversity in soils is determined by soil characteristics such as humidity, temperature, structure, and availability of nutrients for microbial development. In our study, concentrations of microbial biomass C (MBC) were significantly reduced by degradation, demonstrating the sensitivity of MBC to changes in soil caused by forest cutting. These results agree with previous observations of reduced MBC in areas where vegetation cover was recently removed (Balota et al., 2003).

Garcia et al. (2002) observed that removal of vegetation cover affects soil chemical and microbiological characteristics, as evidenced by reductions in MBC, BR, and qCO_2. Kaschuk et al. (2010), carrying out studies of soil microbial biomass in Brazilian ecosystems over three decades, found MBC values ranging from 72 to 385 mg C kg^{-1} in Caatinga forest soils. Finally, reductions in MBC due to loss of vegetation cover were also observed by Bastida et al. (2006), in studies of soil microbial activity in degraded semiarid regions of Spain.

Higher microbial BR may be associated with greater biological diversity, via acceleration of the decomposition of organic residues and the release of available nutrients for plant growth. In other words, the level of microbial activity in soils is directly related to the level of inputs of organic residues, beyond soil chemical and physical properties. In addition, areas where vegetation has been preserved the longest have the most favorable levels of soil humidity for microbial development (Balogh et al., 2011). Our results are consistent with those of Martins et al. (2010), who reported higher soil BR rates in areas of undisturbed woody vegetation (3.2 mg CO_2-C kg^{-1} soil h^{-1}) than in areas of moderate or degraded vegetation cover (approximately 2 mg CO_2-C kg^{-1} soil h^{-1}). The trends at our sites are similar, even though the actual rates were considerably lower—no doubt because the soils are sandier and thus do not support higher levels of microbial activity. Finally, Garcia et al. (2002), working in a Mediterranean ecosystem, reported BR values similar to those of our study area (values ranged from 0.5 mg CO_2-C kg^{-1} soil h^{-1} where vegetation cover was low to 1.3 mg CO_2-C kg^{-1} soil h^{-1} where vegetation cover was high. In other words, BR is a particular property of each soil and reflects the status of biological activity under the specific conditions of that soil.

Our results show that the contribution of MBC to soil C (qMIC) was just under 1% for recently cut sites and over 2% for the sites that have remained undisturbed for the longest periods. Jenkinson and Ladd (1981) report that, under normal conditions, MBC represents 1–4% of total organic C. Generally, qMIC values of less than 1% may be attributed to the presence of some limiting factor on microbial biomass activity. For example, we believe that the scarcity of litter inputs at our recently cut sites severely limits the growth of microbial biomass. We also observed an inversion in qMIC between the 0–5-cm and the 5–10-cm depth intervals: values at the recently cleared sites were highest in the 0–5-cm depth interval, whereas those at the sites that had not been cleared for long periods (25 years, 50 years, and 80 years) were highest in the 5–10-cm depth interval. While the differences aren't large, this inversion may suggest that humification in the recently cleared sites is impaired and that mineralization processes are predominating in the 5–10-cm depth interval, since the addition of organic matter by vegetation generally promotes increase in litter. With the addition of organic matter and consequent reduced stress by vegetation maintenance as soils recover from disturbance, microbial biomass is expected to increase, leading to higher qMIC (Wardle and Ghani, 1995).

Interestingly, qCO_2 values declined as time since cutting increased along the Caatinga forest sequence. Biological activity results should be interpreted with caution, however, because low qCO_2 values do not always indicate undesirable conditions (Parkin et al., 1996); in fact, they may indicate more favorable environments for microbial activity (Jakelaitis et al., 2008, Fialho et al., 2006). Greater limitation from other resources (like lack of N) can increase qCO_2 (Spohn 2015). Our results are therefore consistent with not only decreased total inputs of organic matter, but a decline in the quality of those inputs associated with more frequent tree harvesting.

5.6. Recovery time

All the soil properties analyzed in our study have indicated improving conditions with time after vegetation cutting. In evaluating degraded areas, as many as possible of these properties should be considered together as a basis for determining the most favorable time intervals between cutting campaigns. In Caatinga forest zones, where water stress is widespread, vegetation requires longer periods to regenerate—making it critical to establish how much recovery time is needed.

The effects of forest cutting in Caatinga areas—losses of nutrients, soil C, and microbial activity—highlight the need for greater care in exploiting this environment. Such losses are likely to be higher if forest products are removed at even shorter time intervals. Our results consistently suggest that in order to recover lost C storage and preserve biological activity in forest soils, the time intervals between clearing campaigns should be longer than those currently prescribed by most forest management plans in Brazil. For example, Althoff et al. (2016)

used the Century model to simulate the impact of climate change on vegetation growth and soil organic C stock in a Caatinga area, under four different cutting scenarios: a single cutting every 10 years; cutting every 15 years; and cutting every 20 years (in each case with and without burning of the residues). The researchers concluded that under current climate conditions, the vegetation would need 50 years to recover its original biomass, and therefore the currently recommended cutting cycle (10–20 years) is insufficient for recovery.

Further, according to the authors, if the climate changes as predicted, even without further cutting there will be a 40% decrease in Caatinga native vegetation biomass and a 13% decrease in soil organic C by century's end. With such a scenario, cutting the vegetation every 10, 15, or 20 years would reduce production after each consecutive cycle and make sustainable production of firewood impossible. These modeling-based conclusions are consistent with our findings and support our recommendation that for areas with similar environmental conditions (climate, soil, and vegetation), forest management legislation should mandate a longer interval between cutting campaigns.

As an example, when vegetation is cut at 20-year intervals, C concentrations in soils and humic fractions at all the depth intervals are able to recover only to about 32% of their former levels. To achieve maximum (100%) recovery would require an average interval of about 65 years. Critical C fractions in the soils change as a function of cutting times, and some C pools require more time for recovery than others. Nevertheless, in all cases time to recovery is much longer than the 15 years currently allowed between cutting campaigns by Brazilian legislation (CPRH, 2000, 2008). In 15 years, none of the variables we investigated would recover even to 50% (actual recovery times of course would vary depending on the sensitivity of a given variable to disturbance). In other words, our results clearly demonstrate that subjecting Caatinga forests to cutting every 15 years poses a significant environmental problem, threatening continued forest productivity and soil quality. Findings of other studies of Caatinga forest areas in Pernambuco State, Brazil, support this conclusion (Sobrinho et al. (2016).

In conclusion, our results show that forest management practices in semiarid northeastern Brazil have brought about declines in soil C storage and a consequent suppression of soil microbial activity. The C recovery times estimated on the basis of our results indicate that leaving at least six decades between cutting campaigns could enable the recovery of Caatinga forest soils to near-stable conditions, similar to those of forests that have not been cut. Even to achieve 50% recovery would require at least 33 years between cutting campaigns. In the context of mitigating climate change on a global scale, forest management entities should significantly lengthen cutting intervals in semiarid regions; our estimates could serve as a guideline for a new government management plan designed to achieve sustainability for Caatinga forest regions.

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